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ABSTRACT

Researchers, commentators, and politicians have devoted steadily more attention to infrastructure in response to claims that inadequate accumulation of public capital has contributed to substandard U.S. economic growth. Despite this, the link between infrastructure and productivity growth remains controversial. In this regard, it is somewhat surprising that infrastructure research has developed in isolation from the large literature on economic growth. We develop a neoclassical growth model that explicitly incorporates infrastructure and is designed to provide a tractable framework within which to analyze the empirical importance of public capital accumulation to productivity growth. We find little support for claims of a dramatic productivity boost from increased infrastructure outlays. In a specification designed to provide an upper bound for the influence of infrastructure, we estimate that raising the rate of infrastructure investment would have had a negligible impact on annual productivity growth between 1971 and 1986.

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1. INTRODUCTION

In recent years, researchers, commentators, and politicians have devoted steadily more attention to the quality, quantity and financing of infrastructure capital in the United States. At the heart of this debate is the notion that infrastructure is an important input to economic growth, with many participants in the debate attributing (at least in part) substandard United States economic growth in recent years to inadequate accumulation of infrastructure capital.

Not surprisingly, there has also been a sharp increase in research into the economic impact of public sector capital. In an influential study, Aschauer [1989] included public sector capital in an aggregate production function and found that it exerted a very large influence on private sector productivity.[1] (Munnell [1990b], Garcia-Mila and McGuire [1992], and Eberts [1986, 1990] reported qualitatively similar--if smaller--findings.) More recently, estimates of state-level cost functions suggest that public infrastructure is a cost-saving input for manufacturing industries (see, e.g., Morrison and Schwartz [1992]). However, the finding that public sector capital accumulation has been a significant drag on U.S. productivity growth is not uncontroversial. Holtz-Eakin [1994] and Hulten and Schwab [1991], for example, argue that the macroeconomic impact of public sector capital on private productivity has been small.

Concern over the pace of U. S. economic growth has motivated this line of research. In this light, it is somewhat surprising that infrastructure research has developed in isolation from the large literature on economic growth.[2] The purpose of this paper is to take a step toward closing this gap. In the remainder, we develop a neoclassical growth model that explicitly incorporates infrastructure as a component of aggregate production. Our specification is designed to provide a tractable framework within which to analyze the empirical importance of public capital accumulation for productivity growth. Moreover, because of the interest in the contribution of infrastructure provision to economic growth our framework is designed to emphasize this issue, and thus provide a guide to the largest plausible effect from this source.

Section 2 describes the basic framework, specifies the role of public capital in our model of the economy, and describes the evolution of public capital. In Section 3, we analyze the evolution and steady state of the economy under our assumptions. In the following section, we use panel data for the 48 contiguous states between 1971 and 1986 to examine the degree to which the states' growth experiences are consistent with the predictions of our model. Focusing on the states is attractive because the results are of direct importance to the design of state and local government policies. Also, the free flow of technology across state borders makes the assumption of identical production technologies more tenable; the legal setting, political institutions, and tastes do not vary greatly across states; and state data offer the opportunity to analyze reasonably large samples collected on a consistent basis. But state data present difficulties as well. In particular, states are open economies with relatively free mobility of factors. Hence in our empirical work we guard against the endogeneity of labor force growth and investment patterns that mobility potentially engenders.

To anticipate the major results, we find that even in those specifications in which infrastructure enters the estimated production process significantly, there is little support for claims of a dramatic productivity boost from increased infrastructure outlays. For example, in the specification designed to provide an upper bound for the influence of infrastructure capital, we estimate an output elasticity of 0.10. However, even this estimate implies that raising the rate of infrastructure investment by 10 percent would have had a negligible impact on annual productivity growth between 1971 and 1986. The final section is a summary, with suggestions for further work in this area.

2. INFRASTRUCTURE ACCUMULATION

We follow the lead of others and specify the stock of public sector capital as a component of the aggregate production function.[3] With an eye toward the empirical work to follow, we assume that the production function takes the form:

$$Y_t = K_t^{\alpha} G_t^{\beta} (\psi_t L_t)^{1-\alpha-\beta} \tag{2.1}$$

where Y_t is total output, K_t is private capital, G_t is public capital, L_t is the physical quantity of labor, ψ_t is an index of technical efficiency that transforms physical units into effective units of labor, and t denotes time periods.[4] We assume that ψ_t grows at the constant rate λ, so:

$$\psi_t = \psi_0 e^{\lambda t}. \tag{2.2}$$

Similarly, L_t is assumed to grow at the constant rate η. Dividing all variables by the effective quantity of labor yields the production function in intensive form:

$$y_{et} = k_{et}^{\alpha} g_{et}^{\beta} \tag{2.3}$$

where the subscript "e" denotes quantities per effective labor unit.

Of central focus in the recent policy debate has been the fraction of resources devoted to infrastructure investment. We summarize the propensity to invest in the public sector by

θ, the fraction of output devoted to public sector capital accumulation. If we let δ denote the geometric rate of depreciation of capital, then public capital evolves according to the identity:

$$\dot{G}_t = \theta Y_t - \delta G_t \tag{2.4}$$

where the "$\cdot$" denotes derivatives with respect to time. Accordingly, the growth rate of g_{et} may be written as:

$$\frac{\dot{g}_{et}}{g_{et}} = \theta\left(\frac{y_{et}}{g_{et}}\right) - (\eta + \lambda + \delta) \tag{2.5}$$

or,

$$\frac{\dot{g}_{et}}{g_{et}} = \theta k_{et}^{\alpha} g_{et}^{\beta - 1} - (\eta + \lambda + \delta)\ . \tag{2.6}$$

Equation (2.6) summarizes the dynamics of public capital accumulation. In the next section, we turn to the behavior of the economy as a whole.

3. EVOLUTION AND STEADY STATE OF THE ECONOMY

To close the model, we must specify the accumulation of private capital. A detailed investigation of private investment behavior is beyond the scope of this paper; there exists a large literature that focuses on this topic alone. Our strategy is to simply control for private sector capital accumulation, without positing a specific model of the interaction between private investment and the evolution of public capital.[5] Such an approach has both merits and drawbacks. One advantage is that it simplifies the analysis. But it also restricts one to analyzing the behavior of public capital and economic growth *conditional* upon the level of private capital, a drawback that precludes evaluating the degree to which public capital enhances private investment. At the same time, nearly all other empirical analyses in this area make a similar assumption. Following this convention allows us to identify the extent to which an explicitly dynamic framework affects the analysis of infrastructure, while leaving other aspects of the analysis unchanged.

3.1 Characteristics of the Steady State

The long-run tendencies of the economy may be gauged by examining the steady state of the growth model. Setting the growth rate of public capital in equation (2.6) equal to zero, and solving for the steady state value yields:

$$g_e^* = \left(\frac{\theta}{\eta + \lambda + \delta}\right)^{\frac{1}{1-\beta}} (k_e)^{\frac{\alpha}{1-\beta}} \tag{3.1}$$

where the superscript "*" denotes steady state levels. One can use equations (3.1) and (2.3) to predict the steady-state level of labor productivity:

$$y_e^* = \left(\frac{\theta}{\eta + \lambda + \delta}\right)^{\frac{\beta}{1-\beta}} (k_e)^{\frac{\alpha}{1-\beta}} \ . \tag{3.2}$$

Thus, this simple approach leads one to expect that persistent, long-run differences in the level of infrastructure per worker and productivity will be directly related to the propensity to invest in public capital (θ). Moreover, the closeness of the correlation between g_e and y_e will be a direct function of the size of β. That is, setting $\beta = 0$ in equation (3.2) indicates that θ does not affect productivity, although it continues to (in part) determine g_e^*.

3.2 Characteristics of the Growth Path Toward the Steady State

It is useful to extend the theory to develop predictions concerning the path of the economy as it converges toward the steady state. Equation (2.6) describes the accumulation of public sector capital on the path toward the steady state. To make clearer its implications for economic performance, consider a log-linear approximation to the equation in the vicinity of the steady state. Using log-differences as growth rates, the left side of (2.6) is approximately:

$$\frac{\dot{g}_{et}}{g_{et}} \approx \ln(g_{et+1}) - \ln(g_{et}) \quad . \tag{3.3}$$

Similarly, a first-order approximation to the right side of (2.6), evaluated at the steady state values, yields:[6]

$$\theta(k_{et}^{\alpha})(g_{et}^{\beta-1}) - (\eta+\lambda+\delta) \approx (1-\beta)(\eta+\lambda+\delta)\left(\ln(g_e^*) - \ln(g_{et})\right) . \tag{3.4}$$

Combining these results, the growth of public capital is described by:

$$\ln(g_{et+1}) = \phi \ln(g_e^*) + (1-\phi)\ln(g_{et}), \tag{3.5}$$

where:

$$\phi = (1-\beta)(\eta+\lambda+\delta) \quad . \tag{3.6}$$

By iterative substitution into equation (3.5), the level of public capital at time t may be described as a point along the growth path from the initial level of public capital, g_{e0}, toward the steady state. That is:

$$\ln(g_{et}) = \left(1-(1-\phi)^t\right)\ln(g_e^*) + (1-\phi)^t\ln(g_{e0}) \quad . \tag{3.7}$$

Re-arranging equation (3.7) yields the familiar prediction of convergence in a neoclassical growth model:

$$\ln(g_{et}) - \ln(g_{e0}) = \left(1-(1-\phi)^t\right)\left(\ln(g_e^*) - \ln(g_{e0})\right) \quad . \tag{3.8}$$

That is, the growth rate of public capital between *t=0* and *t=t* is inversely related to the initial level of public capital, *ceteris paribus*.[7]

It is useful to think of ϕ as a measure of the speed by which the economy converges to the steady state; i.e., indexing the fraction of the distance to the steady state that is travelled each period. To gain a feel for the magnitudes, consider the time necessary to close 50 percent of the gap between the initial level of public capital and the steady state value by evaluating equation (3.8) under the assumption that:

$$\ln(g_{et}) - \ln(g_{e0}) = 0.50\left(\ln(g_e^*) - \ln(g_{e0})\right) \quad . \tag{3.9}$$

If population and technology each grow at 2 percent per year ($\eta=\lambda=0.02$), depreciation is 5 percent annually ($\delta=0.05$), and $\beta=0.05$, then the implied adjustment speed is 0.086. Under these parameter values, the time required to adjust one-half of the way to the steady state is just under 8 years. A higher value of β raises the time necessary to reach the steady state; if $\beta=0.25$, $\phi=0.068$ and the corresponding time is roughly 10 years.[8]

Our specification of the growth model deliberately emphasizes the role of infrastructure. Indeed, in this specification the productivity of infrastructure (as measured by β), and the size of ϕ dictate the dynamics of the economy. Specifically, differentiating (3.8) and using (2.3) indicates that the effect of devoting greater resources to infrastructure on productivity growth is given by:

$$\frac{d(\ln(y_{et}) - \ln(y_{e0}))}{d\theta} = \beta(1-(1-\phi)^t)\, k_e^{\alpha}(g_e^*)^{\beta-1}. \tag{3.10}$$

The larger the value of β, given ϕ, the greater the direct impact of public-sector capital outlays on productivity growth. Similarly, the larger the value of ϕ, the greater is the effect of increasing the infrastructure investment rate. In general, however, the effect on productivity growth depends upon the full set of parameters in the model.

3.3 Open-Economy Considerations

The discussion thus far has treated each state as if in isolation. In practice, however, states are open to flows of factors of production. How do these considerations affect the analysis? To the extent that infrastructure investment induces flows of capital and labor, these variables will be correlated. The correlation among these variables, however, will not bias efforts to identify the impact of infrastructure on productivity. However, to the extent that high-productivity states attract factors, the direction of causality will be reversed, and econometric inferences contaminated. In the empirical work that follows we attempt to gauge the degree to which the results reflect these influences. Notice, however, that the most likely scenario is that higher productivity permits a state to invest more in infrastructure, leading to an upward bias. Hence, to the extent that we are unsuccessful in controlling bias due to simultaneity, the results are likely to overstate the importance of infrastructure to productivity growth.

4. ECONOMETRIC IMPLICATIONS AND TESTS

The model of infrastructure and economic growth developed above yields strong econometric predictions. Indeed, the model predicts that the accumulation of public capital is *the* source of intensive economic growth, conditional upon the level of private capital. Accordingly, differences in output or productivity are the direct consequence of differences in policies toward infrastructure, a hypothesis that we test using data on the 48 contiguous U.S. states. (The data are described in the Appendix.)

To do so, let i denote states. We must transform the predictions of the theory regarding capital and output per *effective* labor unit (which are not observable) into testable statements regarding capital and output per worker. Let g_t denote public capital per worker, and recognize that:

$$\ln(g_{et}) = \ln(g_t) - \ln(\psi_t) = \ln(g_t) - \ln(\psi_0) - \lambda t \ , \qquad (4.1)$$

which provides a link between effective and observable quantities of public capital. In a similar fashion, one may convert private capital and output from effective to observable units.

4.1 Steady-State Predictions

To begin, we look at the long-run tendencies predicted by the model. Taking the logarithm of both sides of equation (3.1) and transforming variables into observable quantities yields:

$$\ln(g_i) = \frac{1-\alpha-\beta}{1-\beta}(\ln(\psi_0)+\lambda t) + \frac{1}{1-\beta}\ln\left(\frac{\theta_i}{\eta_i+\lambda+\delta}\right) + \frac{\alpha}{1-\beta}\ln(k_i) \ . \qquad (4.2)$$

This suggests a straightforward regression-based test of the theory. Consider a cross-section regression of the form:

$$\ln(g_i) = a_0 + a_1\ln(\theta_i) + a_2\ln(\eta_i+\lambda+\delta) + a_3\ln(k_i) + \varepsilon_{gi} \quad . \tag{4.3}$$

A comparison of equations (4.2) and (4.3) indicates that one should expect a_1 and a_2 to be of equal magnitude and opposite sign. Moreover, each serves as an estimate of $(1-\beta)^{-1}$. Finally, equation (4.2) indicates that both a_1 and a_2 should exceed a_3 in absolute value. Thus, the regression provides a useful way to gauge the relative importance of private capital, public capital, and labor inputs into the growth of state economies.

As a further check on the theory, notice that the production function (2.3) implies:

$$\ln(y_{ei}) = \alpha\ln(k_{ei}) + \beta\ln(g_{ei}) \ , \tag{4.4}$$

which when transformed into observable units yields an equation predicting cross-state differences in output per worker:

$$\ln(y_i) = b_0 + b_1\ln(\theta_i) + b_2\ln(\eta_i+\lambda+\delta) + b_3\ln(k_i) + \varepsilon_{yi} \ . \tag{4.5}$$

Again the theory implies that b_1 and b_2 should be of equal magnitude and opposite sign, although in this instance it does not constrain the relative size of b_3.

Table 4.1 contains the results of checking these predictions against data from the 48 contiguous states for 1986. It is not our intention to assert that the states in 1986 constitute a sample of steady-state observations. Rather, we seek an initial check on the plausibility of the framework: are cross-state differences in productivity correlated with the variables predicted to be of lasting importance?

Consider first the estimates in column (1). The dependent variable is the log of state and local government infrastructure capital per member of the labor force in each state. The empirical measures of θ and η are the average values between 1971 and 1986 of gross infrastructure investment as a fraction of Gross State Product (GSP), and the labor force growth rate, respectively. We assume that $\lambda + \delta = 0.07$.[9] Private capital per worker is based on data in Munnell [1990b].[10]

The initial results generally support the model. The coefficients on θ_i and $(\eta_i + \lambda + \delta)$ are correctly signed, precisely estimated, and of comparable size. Indeed, it is straightforward to constrain the coefficients in accordance with the theory; these estimates are shown in column (2). The coefficient on the private capital variable is positive, smaller than the coefficient on θ, and precisely estimated in both columns. Finally, the fit is relatively good, with an adjusted R^2 over 0.70. In sum, the initial pass at the data suggests that the model provides an empirically promising description of cross-state variation in public sector capital.

In columns (3) and (4), however, we move toward explaining productivity (GSP per worker), and the results are decidedly less favorable. While the private capital variable continues to have its expected sign, and is statistically significant, the remaining point estimates are often of the wrong sign. In addition, the data reject the constraints suggested by the theory at any significance level higher than four percent. (See the row labelled "Test" in column (4).) Finally, the variables explain a relatively small fraction of cross-state variation in productivity. Thus, the simple version of the theory seems relatively successful in explaining public capital accumulation, but provides an unsatisfactory explanation of cross-state differences in productivity.[11]

From another perspective, however, even the results in columns (1) and (2) do not provide evidence that differences in infrastructure policy translate into differences in economic performance. In column (1), a_1 and a_2 each serve to estimate $(1-\beta)^{-1}$, and the implied β's are negative. The same is true for the constrained estimates in column (2).[12] Perhaps not surprisingly, such a simple theory does not provide a powerful explanation of productivity differences across states.

Before leaving these estimates, it is worthwhile to investigate a potential econometric difficulty. A look at equation (4.2) reveals the presence of ψ_0 embedded in the intercept of equation (4.3). (The same is true of (4.5).) One might suspect that there are state-specific characteristics -- location, climate, etc. -- that generate permanent differences in productivity. These differences across states manifest themselves as differences in the initial level of productivity, ψ_{i0}. In turn, these productivity differences may affect the propensity to invest in public capital, the accumulation of private capital, and the growth rate of the labor force. In econometric terms, the equations may be contaminated by the presence of state-specific effects that are correlated with the right-hand side variables, raising the specter of biased and inconsistent parameter estimates.[13]

The theory itself delivers a straightforward means to circumvent this difficulty. One may eliminate ψ_{i0} by taking a linear combination of equations (4.3) and (4.5). Specifically, we may estimate:

$$\ln(g_i) - \ln(y_i) = c_0 + c_1\ln(\theta_i) + c_2\ln(\eta_i+\lambda+\delta) + c_3\ln(k_i) + \varepsilon_i . \quad (4.6)$$

Here, the theory again delivers strong predictions concerning the estimated coefficients, leading one to anticipate $c_1 = -c_2 = 1$ and $c_3 = 0$. The final two columns of Table 4.1 show the results of checking these predictions. In column (5), the estimates of c_1 and c_2 are in rough accordance with the theory. Although one may reject the hypothesis that $c_1 = -c_2 = 1$, the magnitudes are in the right ballpark and one cannot reject $c_1 = -c_2$. The estimate of c_3, however, is clearly very different from the predicted value of $c_3 = 0$.[14]

As discussed in the Appendix, our measure of "infrastructure" is dictated in part by data availability. As a check on the sensitivity of our results to this definition, Table 4.1a shows the implications of expanding the definition of θ to include *all* capital outlays by the state and local governments in each state. Correspondingly, we define the dependent variable to be the log of total state and local govemment capital per worker. Qualitatively, this change in definition has little impact. Indeed, to the extent that there is any effect, these results are marginally closer to the theoretical predictions.

4.2 Growth Path Predictions

The empirical analysis thus far has focused upon the long-run behavior of state economies, as predicted by the steady-state of the growth model. As noted earlier, we may derive a prediction conceming the movement through time of each state economy along the path leading to its steady state (see equation (3.8)). This serves to relax the assumption that all cross-state differences in economic variables are due to differences in their predicted steady states. Instead, we incorporate a second source of variation: cross-differences in the time required to reach the long-run position. These differences may stem from either of two sources. First, the starting point -- the initial level of public capital -- may be higher (or lower) than in comparison states. If all state economies converge to the steady-state at the same rate, a higher starting point would translate directly into a greater level of public capital per labor unit. One would not expect all states to converge at the same rate, however. As noted above (see equation (3.6)), the adjustment speed (ϕ) will differ due to differences in the rate of labor force growth. The result is that states with a faster adjustment process will have greater levels of public capital and output, *ceteris paribus*, at any point in time.

It is possible to put some econometric meat on this theoretical skeleton by converting equation (3.8) into its observable counterpart. Specifically, using (3.8) along with (3.1) and (4.1) yields:

$$\ln(g_{it}) - \ln(g_{i0}) = (1-(1-\phi_i)^t)\left(\frac{1-\alpha-\beta}{1-\beta}\ln(\psi_0) + \frac{1}{1-\beta}\ln\left(\frac{\theta_i}{\eta_i+\lambda+\delta}\right) + \frac{\alpha}{1-\beta}\ln(k_{it}) - \ln(g_{i0})\right)$$
$$- \left(1 - \frac{\alpha}{1-\beta}(1-(1-\phi_i)^t)\right)\lambda t \ . \tag{4.7}$$

Notice that equation (4.7) contains both the cross-sectional differences among states and the time-series variation within each state. Following a similar derivation, we may obtain an equation tracking the dynamics of output growth that stem from the accumulation of public capital. Specifically, our assumptions imply that:

$$\ln(y_{et}) - \ln(y_{e0}) = (1-(1-\phi)^t)\left(\ln(y_e^*) - \ln(y_{e0})\right), \tag{4.8}$$

which may be transformed into:

$$\ln(y_{it}) - \ln(y_{i0}) = (1-(1-\phi_i)^t)\left(\frac{1-\alpha-\beta}{1-\beta}\ln(\psi_0) + \frac{\beta}{1-\beta}\ln\left(\frac{\theta_i}{\eta_i+\lambda+\delta}\right) + \frac{\alpha}{1-\beta}\ln(k_{it}) - \ln(y_{i0})\right)$$
$$+ \left(1 - \frac{\alpha}{1-\beta}(1-(1-\phi_i)^t)\right)\lambda t \ . \tag{4.9}$$

The next set of estimates checks the predictions of (4.7) and (4.9) against our panel of state data.

To begin, consider column (1) of Table 4.2, which displays the results of estimating the linear analogue to equation (4.7) using data for 1986. The dependent variable is the log-difference of infrastructure capital per worker over the period 1971 to 1986. Thus, it measures the cumulative growth rate of public capital per worker over the period. The estimates indicate that growth rises with the average rate of investment in the public sector (θ_i), declines with greater capital needs ($\eta_i+\lambda+\delta$), and increases with the amount of private capital per worker (k_i). Importantly, the negative coefficient on $ln(g_{i0})$ indicates that the data support the notion of convergence in the provision of public capital; growth is inversely related to the initial level of capital. Each of the parameters is significant at conventional levels.

Column (2) repeats the estimation exercise, using instead the cumulative growth in productivity as the dependent variable. A comparison of equations (4.7) and (4.9) reveals the theoretical prediction that each of the estimated coefficients should have the same sign as in column (1), and that the coefficients on θ_i and ($\eta_i + \lambda + \delta$) should be smaller in absolute value. As before, the estimated coefficients generally follow the predictions of the theory, although the precision of the estimates is less than in column (1). The exception is the (negative) estimated coefficient for k_i. Overall, relaxing the constraints placed on the data to permit adjustment toward the steady-state improves the performance of the model in explaining the provision of public sector capital and the resultant level of productivity per worker.

These estimates, however, rely only on the predicted relationship between 1986 and 1971, and thus are based on only a small fraction of the panel data. It is tempting to pool the data for all the available years as a means of exploiting all the available information in the data. In doing so, however, one must recognize that the "coefficients" in these regression will change through time. For example, equation (4.7) indicates that the coefficient on $ln(g_{i0})$ in any year will be $(1-(1-\phi_i)^t)$, which changes through time. To use all the years appropriately, then, one must impose the full set of non-linear restrictions and estimate directly the underlying parameters of the model -- α, β, λ, and ψ_0. Moreover, because equations (4.7) and (4.9) share the same underlying parameters, one may enhance the efficiency of the estimates by estimating these equations jointly.

Columns (3) and (4) of Table 4.2 contain the outcome of this procedure.[15] The estimated elasticity with respect to private capital (α) is 0.32, with an estimated standard error of only 0.01. An estimate of this magnitude is comparable to estimates of the share of capital income in total income, and thus near conventional estimates of the elasticity of output with respect to capital inputs. For our purposes, however, the most interesting result is the estimated β of -0.04. Thus, the less restrictive specification yields the same result as the steady state regressions in Table 4.1: the point estimate of β is negative and significant at conventional levels. To complete the results, the implied estimate of the elasticity of output with respect to labor inputs is 0.73 and the estimated growth in the technical efficiency of labor λ is 0.25 percent annually. The latter is broadly consistent with very slow growth in productivity over the past two decades.

As before, it is desirable to control for the presence of unobserved state-by-state variation in productivity levels. Here, however, the explicit use of the time dimension permits us to adopt a different strategy for eliminating the ψ_{i0} than used in the steady-state regressions above. We begin by explicitly parameterizing the permanent variations in productivity across states by interacting ψ_0 with a dichotomous variable for each state in the sample.

As shown in columns (5) and (6) of Table 4.2, controlling for state-specific differences in productivity in this manner has a dramatic impact on the estimated parameters. The estimate of α falls to 0.07, while that of β rises to just under 0.05. The implied value for the elasticity with respect to labor rises to 0.88, and the estimated growth in technical efficiency, λ, rises to 0.41 percent. In each case, the precision of the estimated coefficient is good.

What should we make of these changes in the estimates? The use of state dichotomous variables effectively identifies the remaining parameters via year-to-year fluctuations about state-specific means. As a result, the large implied elasticity with respect to labor inputs likely reflects the dominance of employment in short-run output fluctuations.[16] A second issue is the degree to which parameters identified in this way are subject to simultaneity bias. Recall that factor mobility across states might lead to circumstances in which relatively high-productivity states attract inflows of capital and labor, thus implying reverse causation. Controlling for state effects eliminates productivity differences across states that do not change through time. This leaves, however, the possibility that changes in productivity over time will lead to simultaneity problems.

Reasoning in this way suggests that if simultaneity is quantitatively important in our data, then the history of productivity in a state should improve one's ability to predict the future path of θ and η. That is, one should find that productivity "Granger-causes" these variables. We investigate this possibility using the estimation and testing procedures developed by Holtz-Eakin, Newey, and Rosen [1988] for vector autoregressions in panel data. Specifically, we specify an equation for θ_{it} that contains a dummy variable for each year, two lags of θ_{it}, two lags of η_{it}, and two lags of y_{it}.[17] The parameters are estimated using instrumental variables to control for the difficulty presented by serial correlation in the error term and the presence of lagged dependent variables.[18] We test the null hypothesis that past changes in y_{it} may be excluded from the equation. The test statistic for this hypothesis, distributed as a chi-square with 26 degrees of freedom, is only 0.42. Thus, we fail to reject the null hypothesis of no causal relation between past changes in states' productivity and the rate of investment. We follow a similar procedure for η_{it}. In this instance, the test statistic, also distributed as a chi-square with 26 degrees of freedom, is 9.7. Once more, we fail to reject the null hypothesis of no causal relation.

Thus, within the context of our empirical analysis, the data do not suggest that the estimate of β is plagued by a great degree of simultaneity bias. Of course, these diagnostics do not constitute a complete investigation of factor mobility across states. For this reason, we also examine an alternative means by which to eliminate state-effects -- by subtracting equation (4.9) from equation (4.7). This approach has a cost, however, k_{it} is eliminated and it is no longer possible to identify α.

Since β is the central parameter for purposes of this study, we proceed in column (7) to estimate the difference between these two equations. In effect, β is identified by examining the degree to which the difference between growth of infrastructure and the growth of output is correlated with the infrastructure investment rate. The resulting parameter estimate is substantially larger than in earlier columns -- roughly 0.10 -- and precisely estimated.

As before, we check the sensitivity of these results to our definition of infrastructure capital by re-estimating the equations using all state-local public capital. These results are presented in Table 4.2a. In general, there are few differences in the parameter estimates. While the point estimates differ, the qualitative nature of the results is robust with respect to alternative measures of the inputs from the public sector. The two tables share a second characteristic. In each case, the model does a relatively good job of explaining variations in infrastructure capital per worker. The fit for productivity, however, is much worse. This pattern of parameter estimates calls into question the importance of infrastructure in explaining productivity growth.

4.3 Implications

What do the estimates imply about the productivity effects of spending on public capital? To explore this issue, we compute the effect on productivity growth of raising the θ for each state by 10 percent, which corresponds to about $10 billion (measured in 1982 dollars) of new spending in 1986. By differentiating equation (4.9) with respect to θ and evaluating using $\beta = 0.10$ and data for 1986, we compute the effect on cumulative productivity growth.[19] As a preliminary, note that the productivity effect depends in part on the adjustment speed, ϕ. We display the estimated values in Table 4.3. The mean value of the adjustment speed is 0.069, with a low value of 0.055 (in Pennsylvania) and a high value of 0.096 (in Arizona). Measuring things slightly differently, the mean numbers of years required to adjust one-half of the way to the steady state is 9.9. Here the range is from 6.8 years in Arizona to 12.4 years in Pennsylvania.

What are the estimated productivity effects? In general, they are quite modest, averaging 1.02 percent. Notice that these are the effects on *total* productivity growth over the 1970 to 1986 period, so that the effect on average annual productivity growth is quite small. Even the maximum effect in the sample -- 1.08 in Arizona -- implies a trivial impact on annual productivity growth. Thus, even if our point estimates are evidence of a qualitatively important role for public sector capital in the production process, they do not suggest a quantitatively important impact on the productivity problem. Moreover, we have deliberately chosen the parameters underlying our calculations to maximize our estimate of the impact.

5. SUMMARY

The purpose of this paper has been to assess the empirical contribution of infrastructure accumulation to productivity growth using an explicit model of economic growth and a panel of state data. To do so, we introduce infrastructure capital into a neoclassical model of economic growth in a fashion symmetric to private capital accumulation, and examine the empirical implications.

From the perspective of public sector capital accumulation, a robust bottom line emerges: the data do not assign an important quantitative role in explaining the growth patterns of states. In this respect, the results echo those of Evans and Karras [1992], Holtz-Eakin [1994] or Hulten and Schwab [1991].

Using the predictions of growth models to guide infrastructure analyses appears to be a promising avenue for further research. As noted earlier, the analysis presented in this paper controls for the level of private capital accumulation, but does not model the interaction between infrastructure and investment incentives. An obvious and important extension, therefore, is estimation of the joint evolution of output, private capital accumulation, and infrastructure accumulation in the context of a well-specified model. Further, in the context of state economic growth, factor mobility is an important issue. For the purposes of this paper, our strategy has been to employ econometric techniques designed to minimize the influences of factor mobility on our estimates. The next step, however, is to develop a framework based on mobile factors to serve as the basis for empirical work.

Table 4.1
"Steady State" Regressions[*]
State-Local Infrastructure Capital

	Dependent Variable					
	ln g Unconstrained (1)	*ln g* Constrained (2)	*ln y* Unconstrained (3)	*ln y* Constrained (4)	*ln g-ln y* Unconstrained (5)	*ln g-ln y* Constrained (6)
$ln\ \theta_i$	0.6483	0.6314[+]	-0.09621	-0.06923[+]	0.7445	0.7006[+]
	(0.1157)	(0.01979)	(0.01163)	(0.01174)	(0.01893)	(0.01912)
$ln\ (\eta_i+\lambda+\delta)$	-0.5012	-0.6314[+]	-0.1382	0.06923[+]	-0.3630	-0.7006[+]
	(0.04625)	(0.01979)	(0.02634)	(0.01174)	(0.04289)	(0.01912)
$ln\ k_i$	0.4889	0.5109	0.2165	0.1815	0.2724	0.3294
	(0.01837)	(0.01706)	(0.01046)	(0.01012)	(0.01704)	(0.01648)
Intercept	-1.855	-2.154	-3.562	-3.084	1.707	0.9297
	(0.1157)	(0.06440)	(0.06591)	(0.03821)	(0.1073)	(0.06222)
Test		0.46		0.04		0.04
Adjusted R^2	0.734	0.731	0.368	0.307	0.735	0.710
N	48	48	48	48	48	48

[*]Variables defined in text. Data sources described in the Appendix. Numbers in parentheses are standard errors.

[+]Constrained to be of equal magnitude and opposite sign. The row labelled "Test" shows the p-value for an F-test of the null hypothesis that the constraint is true.

Table 4.1a
"Steady State" Regressions[a]
All State-Local Capital

	Dependent Variable					
	ln g Unconstrained (1)	*ln g* Constrained (2)	*ln y* Unconstrained (3)	*ln y* Constrained (4)	*ln g-ln y* Unconstrained (5)	*ln g-ln y* Constrained (6)
$ln\ \theta_i$	0.7134 (0.08478)	0.7181[b] (0.08182)	-0.1747 (0.06980)	-0.1485[b] (0.06949)	0.8882 (0.05738)	0.8666[b] (0.05712)
$ln\ (\eta_i+\lambda+\delta)$	-0.7526 (0.1611)	-0.7181[b] (0.08182)	-0.04521 (0.1326)	0.1485[b] (0.06949)	-0.7074 (0.1090)	-0.8666[b] (0.05712)
$ln\ k_i$	0.4169 (0.04955)	0.4145 (0.04807)	0.2010 (0.04079)	0.1873 (0.0407982)	0.2159 (0.03353)	0.2271 (0.03356)
Intercept	-2.278 (0.4044)	-2.188 (0.1777)	-3.623 (0.3330)	-3.115 (0.1509)	1.345 (0.2737)	0.9279 (0.1241)
Test		0.80		0.30		0.42
Adjusted R^2	0.779	0.784	0.342	0.315	0.872	0.866
N	48	48	48	48	48	48

[a]Variables defined in text. Data sources described in the Appendix. Numbers in parentheses are standard errors.

[b]Constrained to be of equal magnitude and opposite sign. The row labelled "Test" shows the p-value for an F-test of the null hypothesis that the constraint is valid.

Table 4.2
Growth Path Equations*
State-Local Infrastructure Capital

	Dependent Variable						
	$\Delta ln\ g$	$\Delta ln\ y$	$\Delta ln\ g$	$\Delta ln\ y$	$\Delta ln\ g$	$\Delta ln\ y$	$\Delta ln\ z$
	1986 Cross-Section		Panel: No Fixed Effects		Panel: Fixed Effects		Panel
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$ln\ \theta_i$	0.5555 (0.05545)	0.01234 (0.02729)					
$ln\ (\eta_i+\lambda+\delta)$	-0.7045 (0.1108)	-0.07487 (0.06543)					
$ln\ k_i$	0.2271 (0.04405)	-0.03195 (0.03135)					
$ln\ g_{i0}$	-0.5693 (0.06436)						
$ln\ y_{i0}$		-0.4812 (0.05357)					
Intercept	-1.494 (0.3021)	-1.846 (0.2158)					
α			0.3160 (0.01030)	0.3160 (0.01030)	0.07461 (0.02717)	0.07461 (0.02717)	
β			-0.03777 (0.01301)	-0.03777 (0.01301)	0.04565 (0.02687)	0.04565 (0.02687)	0.1032 (0.03412)
λ			0.002351 (0.0003199)	0.002351 (0.0003199)	0.004063 (0.0003726)	0.004063 (0.0003726)	0.004836 (0.0006141)
$ln\ \psi_0$			-3.638 (0.02487)	-3.638 (0.02487)			
Adjusted R^2	0.713	0.538	0.726	0.491	0.967	0.557	0.795
N	48	48	768	768	768	768	768

*See notes to Table 4.1. Parameter estimates in columns (3) and (4) are constrained to be equal. Also, the estimates in columns (5) and (6) are constrained to be equal. $\Delta \ln g \equiv \ln g_t - \ln g_0$, $\Delta \ln y \equiv \ln y_t - \ln y_0$, and $\Delta \ln z \equiv \Delta \ln g - \Delta \ln y$.

Table 4.2a
Growth Path Equations*
All State-Local Capital

	Dependent Variable						
	$\Delta ln\ g$	$\Delta ln\ y$	$\Delta ln\ g$	$\Delta ln\ y$	$\Delta ln\ g$	$\Delta ln\ y$	$\Delta ln\ z$
	1986 Cross-Section		Panel: No Fixed Effects		Panel: Fixed Effects		Panel
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$ln\ \theta_i$	0.4710 (0.05783)	0.7763×10^{-6} (0.03805)					
$ln\ (\eta_i+\lambda+\delta)$	-0.5868 (0.09864)	-0.06798 (0.06775)					
$ln\ k_i$	0.2115 (0.03772)	-0.02573 (0.03046)					
$ln\ g_{i0}$	-0.4061 (0.6693)						
$ln\ y_{i0}$		-0.4903 (0.05364)					
Intercept	-0.8408 (0.2922)	-1.812 (0.2214)					
α			0.3124 (0.0101)	0.3124 (0.0101)	0.06727 (0.02720)	0.06727 (0.02720)	
β			-0.01314 (0.01728)	-0.01314 (0.01728)	0.02490 (0.02434)	0.02490 (0.02434)	0.1123 (0.03991)
λ			0.004193 (0.0003536)	0.004193 (0.0003536)	0.005027 (0.0003453)	0.005027 (0.0003453)	0.006170 (0.0005195)
ψ_0			0.02595 (0.0006070)	0.02595 (0.0006070)			
Adjusted R^2	0.650	0.501	0.739	0.481	0.940	0.552	0.681
N	48	48	768	768	768	768	768

*See notes to Table 4.2. Parameter estimates in columns (3) and (4) are constrained to be equal. Also, the estimates in columns (5) and (6) are constrained to be equal. $\Delta \ln g \equiv \ln g_t - \ln g_0$, $\Delta \ln y \equiv \ln y_t - \ln y_0$, and $\Delta \ln z \equiv \Delta \ln g - \Delta \ln y$.

Table 4.3
Estimated Adjustment Speeds and Productivity Effects
By State[*]

State	Adjustment Speed (ϕ)	Productivity Effect	State	Adjustment Speed (ϕ)	Productivity Effect
Alabama	0.0669	1.019	Nebraska	0.0634	1.006
Arizona	0.0963	1.082	Nevada	0.0946	1.080
Arkansas	0.0694	1.028	New Hampshire	0.0810	1.058
California	0.0743	1.042	New Jersey	0.0635	1.006
Colorado	0.0836	1.063	New Mexico	0.0807	1.057
Connecticut	0.0636	1.007	New York	0.0548	0.965
Delaware	0.0639	1.008	North Carolina	0.0692	1.027
Florida	0.0881	1.071	North Dakota	0.0671	1.020
Georgia	0.0757	1.046	Ohio	0.0572	0.978
Idaho	0.0719	1.035	Oklahoma	0.0694	1.028
Illinois	0.0573	0.978	Oregon	0.0717	1.035
Indiana	0.0593	0.988	Pennsylvania	0.0545	0.964
Iowa	0.0597	0.990	Rhode Island	0.0577	0.980
Kansas	0.0669	1.019	South Carolina	0.0686	1.025
Kentucky	0.0662	1.017	South Dakota	0.0622	1.001
Louisiana	0.0686	1.025	Tennessee	0.0690	1.026
Maine	0.0652	1.013	Texas	0.0806	1.057
Maryland	0.0682	1.024	Utah	0.0791	1.054
Massachusetts	0.0630	1.004	Vermont	0.0687	1.026
Michigan	0.0604	0.993	Virginia	0.0732	1.039
Minnesota	0.0692	1.027	Washington	0.0719	1.035
Mississippi	0.0648	1.012	West Virginia	0.0567	0.975
Missouri	0.0629	1.004	Wisconsin	0.0655	1.014
Montana	0.0650	1.012	Wyoming	0.0802	1.056

[*]See text for discussion.

APPENDIX

Output for each state is taken from the estimates of Gross State Product (GSP) produced by the Bureau of Economic Analysis (BEA). The labor force for each state was constructed from data on unemployment rates and total employment, also from the BEA. Productivity is defined as the ratio of output to the labor force. Real private-sector capital in each state is taken from Munnell [1990]. The estimates of investment in infrastructure are based on real capital investment for state and local governments from Holtz-Eakin [1993a]. "Infrastructure" is defined as capital devoted to streets and highways, sanitation and sewage, and electric, gas, and water utilities, while "all capital" encompasses all capital owned by the state and local governments in a state. Sample statistics for the data are shown in Table A1.

Table A1
Descriptive Statistics

Variable	Mean (Standard Deviation)
Investment Rate (θ)	
Infrastructure	0.190 (0.00625)
All Capital	0.0345 (0.00783)
Labor Force Growth Rate (η)	0.0258 (0.0133)
Initial Levels (1970)	
Log Output Per Worker ($ln\ y_0$)	-3.59 (0.193)
Log Public Capital Per Worker ($ln\ g_0$)	
Infrastructure	-4.81 (0.296)
All Capital	-4.36 (0.213)
Cumulative Growth (1970-1986)	
Output Per Worker ($ln\ y_t - ln\ y_0$)	0.0493 (0.0739)
Public Capital Per Worker ($ln\ g_t - ln\ g_0$)	
Infrastructure	-0.0802 (0.115)
All Capital	-0.0171 (0.0920)
Log Private Capital Per Worker ($ln\ k$)	-3.66 (0.173)

NOTES

1. Indeed, Aaron [1992] and Hulten and Schwab [1991] argue that the impacts are implausibly large.

2. Duffy-Deno and Eberts [1989] estimate dynamic equations to quantify the impact of public sector capital spending. They do not, however, explicitly link their empirical investigation to a model of economic growth.

3. See, for example, Aschauer [1989], Munnell [1990], Holtz-Eakin [1994], or Morrison and Schwartz [1992].

4. Holtz-Eakin [1994] finds that the data is consistent with the constant returns to scale assumption in (2.1). Also, the results in Young [1992] argue against a specification with increasing returns to scale in capital inputs.

5. With an eye toward factor mobility, we experimented with a specification in which the adjustment of private capital was not costly, and capital flows instantaneously equated the net (of taxes and depreciation) return to the marginal investment in all locations. In this context, taxes reduce the incentive to invest, while infrastructure raises the marginal product of private capital, and hence raises investment incentives. In practice, however, the assumption of instantaneous adjustment appears too extreme to capture the dynamics of state-by-state capital accumulation, leading to computational difficulties and implausible parameter estimates.

6. Complete derivations of all results are available from the authors.

7. See Mankiw, Romer, and Weil [1992] for an investigation of the convergence hypothesis in an international context. Holtz-Eakin [1993b] follows a similar approach using state data.

8. In the limit, when β is equal to 1, ϕ is equal to 0. As a result, the economy does not converge to a steady state. Instead it grows continuously at a rate directly related to θ. See below.

9. The results are not sensitive to this assumption.

10. We thank Alicia Munnell for providing these data to us.

11. An alternative strategy for checking the long-run predictions is to use the (steady state) condition that the private capital-output ratio is constant to eliminate k_i from the regressions. This approach yields results essentially the same as those in Table 4.1. For example, in the analogue to column (1) of the table, the coefficient on θ_i is 0.83 and that on $(\eta_i + \lambda + \delta)$ is -0.61. Moreover, the data do not reject the constraints; the constrained point estimate is 0.81 with a standard error of 0.096. As in the table,

explaining productivity is less successful; both coefficients are of the wrong sign and insignificant. We thank a referee for suggesting this approach.

12. Holtz-Eakin [1994] often finds point estimates of β to be negative (while insignificant) in his estimates of state production functions.

13. Holtz-Eakin [1994] emphasizes the importance of controlling for state-specific effects.

14. As above (see note 11), we estimated the differenced equation (comparable to column (6)) imposing a constant private capital-output ratio. The estimated coefficient is 0.89 (with a standard error of 0.065), which is close to the predicted value of 1.0. In general, however, imposing more theoretical structure on the cross-state regressions does not alter our conclusion: the variables suggested by the theory are relatively successful in explaining public capital accumulation, but unsuccessful in predicting differences in productivity.

15. The equations were estimated using a non-linear, seemingly unrelated regressions (SUR) technique.

16. Holtz-Eakin [1994] reports a similar phenomenon.

17. The results are not sensitive to the lag length chosen for the vector autoregression.

18. See Holtz-Eakin, Newey, and Rosen [1988] for details. We use lags two and three of θ_{it}, η_{it}, and y_{it} as instrumental variables and do not constrain the coefficients of the equation to be time-invariant.

19. In the computations, we set $\delta = 0.05$, $\lambda = 0.04063$, and η equal to the average labor force growth rate between 1971 and 1986.

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